NUCLEAR ENERGY RESEARCH INITIATIVE

An Innovative Transport Theory Method for Efficient Design, Analysis, and Monitoring of Generation IV Reactor Cores

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The current generation of core neutronics methods are based on nodal diffusion theory and utilize homogenized cross sections and other physics data generated by single assembly, infinite medium transport theory calculations. This reactor-analysis methodology was developed and refined for the currently operating class (Generation II) of light water reactors (LWRs). Until about a decade ago, the reload cores of these reactors were designed with relatively homogeneous distributions of fuel, moderator, and absorber materials. For these systems, core-level diffusion theory is a good approximation, and the computational de-coupling of fuel assemblies for generating physics data is acceptable.

The current trend in LWR cores, however, is toward higher degrees of heterogeneity. In order to lengthen operating cycles, recent cores have been designed with higher amounts of total fissile mass, which has necessitated the addition of burnable absorbers to hold down the reactivity at the beginning of core life. Increased fuel utilization has been achieved by varying the fuel enrichment within assemblies and optimizing the arrangement of assemblies with significantly different fissile and fission product compositions. It is reasonable to expect these or similar design features to be present in the Generation IV light water reactors due to the unchanging desire to increase plant availability and reduce cost.

The trend toward compositional heterogeneity in LWRs and the desire for smaller, modular reactors in the Generation IV class will lead to cores with higher neutron flux gradients, resulting from increased core surface area to volume ratios in the latter case. In these systems, the neutron leakage between adjacent assemblies is significant and cannot be neglected. Generating physics data using single assembly infinite medium transport calculations, as is done with current core neutronics methods, may lead to substantial errors in the homogenized cross sections and discontinuity factors. Without accurate data, the simplified nodal core model will produce inaccurate results. This is the consequence of the computational de-coupling of a highly coupled system.

Non-LWR Generation IV reactor designs are likely to be so different from current LWRs that they will necessitate a different (and probably smaller) set of assumptions on which to base core neutronics models. For example, in the pebble-bed modular reactor (PBMR), a high degree of uncertainty exists in the distribution of fissile mass among localized core regions due to the movement of pebbles with different degrees of burn-up as well as the presence of pebbles that contain only graphite. Further uncertainties resulting from the use of computational methods based on approximations to transport theory with limited ranges of validity will only exacerbate this problem. In addition, accurate calculations in localized portions of the PBMR cores must be performed in three spatial dimensions due to the complex geometry of packed arrangements of spherical pebbles. This aspect of PBMR cores creates problems for the current methods based on two-dimensional transport calculations applied to LWRs in which the variation of core properties in the vertical (third) dimension is relatively weak.

It is clear that the next generation of reactor analysis methods will be based largely on transport theory (both at the assembly and core levels) and involve fewer approximations regarding the nature of the core system than current methods. Diffusion theory and the multitude of methods based on transport corrections to diffusion theory will not be sufficient to support the optimum design, operation, and monitoring of the next two generations of reactor systems for the reasons delineated above. A computationally efficient core-wide transport theory method would provide a highly accurate and flexible design tool (i.e., applicable to a much broader class of systems). In addition, from an engineering standpoint, it would support the pursuit of maximal increases in fuel utilization and plant availability and decreases in operating margins, the probability of fuel damage, and spent fuel inventory. These are many of the advantages sought in the Generation IV class—all of which lead to reduced overall costs.

The currently available transport theory methods have had limited success when applied to core-level calculations, and nearly all require the homogenization of assembly-level physics data. It is proposed that a next-generation, high-order variational coarse-mesh transport method be developed that does not require any homogenization or the use of discontinuity factors. The method is developed by deriving equations from a variational principle that admits discontinuous trial functions. Surface Green's functions are used for the spatial basis within each coarse-mesh and include all of the local transport characteristics as opposed to polynomial or other simple basis sets. Preliminary work in one-dimensional slab geometry with discrete ordinates and multigroup cross sections has been completed and demonstrates the feasibility and promise of the approach. The fine-mesh results are reproduced exactly by the coarse-mesh method in the test problems. Integral to the proposed method, and therefore requiring no additional development, is the procedure for flux reconstruction at the detail of the fine-mesh calculations. The speed of the core calculation in higher dimensional geometries is expected to be close to that of current methods so that it can be used for design and core monitoring calculations.

The objective of the project is to develop the transport theory method and implement it for advanced and Generation IV LWRs and for the PBMR. The work will be accomplished through the collaborative effort of three organizations: Georgia Institute of Technology, Idaho National Engineering and Environmental Laboratory (INEEL), and Oak Ridge National Laboratory (ORNL). Georgia Tech will lead the project, develop the transport method, and implement the method for LWR calculations; INEEL will provide expertise in the area of PBMR calculations, and couple a coarse-mesh computational module to their pebble transport (movement) code; and ORNL will provide expertise in performing efficient and accurate transport calculations for both reactor types.